Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter

Jacek Chowdhary,[1] Brian Cairns,[1] Michael Mishchenko, and Larry Travis
NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025

Abstract. The evaluation of the direct and indirect aerosol forcings of climate requires precise knowledge of the aerosol optical thickness, size distribution, chemical composition, and number density. Global monitoring of these parameters from satellites requires instruments that make full use of the information content of the scattered solar radiation. In this paper we analyze multispectral and multiangle photopolarimetric observations performed with an airborne version of the Earth Observing Scanning Polarimeter over the ocean and demonstrate their exceptional retrieval potential. Using the 0.865- and 2.250-µm channels, we are able to determine the parameters of a bimodal size distribution, identify the presence of water-soluble and sea salt particles, and retrieve the optical thickness and column number density of aerosols. We also demonstrate that less comprehensive measurements by existing instruments would fail to provide retrievals of comparable completeness and accuracy.

1. Introduction

Radiative balance calculations suggest that the aerosol climate forcing can be comparable in magnitude but opposite in sign to that of anthropogenic greenhouse gases [*IPCC*, 1996]. However, the exact magnitude and even the sign of the total aerosol forcing remains one of the largest unknown factors in climate research [*Hansen et al.,* 1998]. The reliable evaluation of the direct and indirect aerosol forcings of climate requires precise knowledge of the global distribution of the aerosol optical thickness, size distribution, chemical composition, and number density [*Lacis and Mishchenko*, 1995]. The only operational aerosol product available so far has been the optical thickness retrieved over the ocean using channel-1 radiances from the Advanced Very High Resolution Radiometer (AVHRR) [*Stowe and Ignatov*, 1997]. However, this product is inherently limited in its accuracy because of the inability of a single-channel, single-viewing-angle algorithm to constrain all parameters of the highly variable, multi-component atmosphere-ocean system. Although it may be possible to improve the accuracy of the optical thickness retrieval and also to determine the aerosol Ångström exponent by including AVHRR channel-2 radiances [*Higurashi and Nakajima*, 1999], the results remain sensitive to multiple untested assumptions made in the retrieval [*Mishchenko et al.*, 1999]. New satellite instruments such as the MODerate resolution Imaging Spectrometer (MODIS) [*King et al.*, 1992], the Multiangle Imaging Spectro-Radiometer (MISR) [*Diner et al.*, 1991], and the POLarization and Directionality of Earth Reflectances (POLDER) instrument [*Goloub et al.*, 1999, *Mukai and Sano*, 1999] provide more comprehensive measurements than AVHRR (Table 1). Nonetheless, they are likely to be unable to fully resolve the non-uniqueness problem associated with passive aerosol retrievals from space, nor can they determine the aerosol parameters with the accuracy necessary for long-term monitoring of climate forcings and feedbacks [*Hansen et al.*, 1995]. In particular, instruments like MODIS and MISR are unlikely to provide sufficiently accurate information on the aerosol composition, size distribution, and column number density [*Mishchenko et al.*, 1997a]. However, this information is crucial for evaluation of the aerosol indirect effect, studies of aerosol formation, processing, and transport, and monitoring the anthropogenic component of the aerosol forcing. Long-term monitoring of aerosols from space requires more advanced instruments that make full use of the spectral, polarization, and angular information content of the scattered solar radiation.

In this paper, we discuss aerosol retrievals over the ocean using data collected with the Research Scanning Polarimeter (RSP) [*Cairns et al.*, 1999]. This instrument is an airborne version of the Earth Observing Scanning Polarimeter (EOSP) [*Travis*, 1993] and provides high-precision, multi-angle measurements of polarization as well as intensity in a wide spectral range from the visible to the infrared. It combines and surpasses the aerosol measurement capabilities of MODIS, MISR, and POLDER. While MODIS has similar spectral coverage, it does not provide multi-angle measurements of a scene. Although MISR and POLDER provide multi-angle coverage, their spectral range is limited to the visible and near infrared (Table 1). By analyzing actual data and comparing the retrievals made using different subsets of data we show that the type of measurements made by RSP can help to resolve the non-uniqueness of aerosol retrievals, while other more limited sets of measurements (MODIS, MISR and POLDER) must rely on the use of prior assumptions.

2. RSP Data and Simulations

The RSP measures the first three Stokes parameters, *I*, *Q* and *U*, in a total of nine spectral channels simultaneously at each viewing angle as the 0.8° instantaneous field of view (IFOV) is continuously scanned, with a 90° swath of measurements (±45° from nadir) being available in the current study. The measurements have a wide dynamic range (14-bit digitization) and high signal to noise ratio (2000 at a reflectance of 0.3) with a radiometric uncertainty of 5% and polarimetric uncertainty of less than 0.2% [*Cairns et al.*, 1999]. The data that are analyzed in this study were acquired over the ocean (several km from the coast) near Morro Bay and above the Santa Barbara Channel, California with the RSP mounted on an aircraft (3km altitude, 50 m/s speed) and the scanner oriented along the direction of the aircraft ground track such that successive nadir views were one IFOV apart and the same point at the ground was seen from multiple viewing angles. Our study is focused on two RSP spectral channels centered at 0.865 and 2.250 µm because coastal waters tend to have high concentrations of inorganic particles that limit the utility of measurements at shorter wavelengths for the purposes of aerosol retrievals [*Gordon*, 1997; *Tanré et al.,* 1997]. Similar channels are available on MODIS, whereas the 0.865-µm channel is the longest one on MISR and POLDER. To simulate the radiation field observed by the airborne RSP, we divide the atmosphere into two layers: A purely molecular layer above the aircraft and a layer below consisting of a homogeneous mixture of molecules and aerosol particles. This simple vertical structure is reasonable for the viewing geometries and channels used in this study and for the suppressed marine boundary layer that we observed, which typically contains most of the aerosol load. In general, we assume that the aerosol population is bimodal [cf. *Nakajima et al*., 1996], each mode (fine and coarse) characterized by its own log normal size distribution and refractive index. The reflectance of the ocean surface is calculated using the geometrical optics approach and assuming the wind-speed-dependent surface slope distribution derived by *Cox and Munk* [1954]. No white caps were observed on the day the data were taken and so foam reflectance is not included in our model. The single-scattering properties of the aerosol particles are obtained from the Mie theory, i.e. a starting assumption of spherical particles, and are assumed to be non-absorbing. Multiple-scattering computations are performed using the fast and accurate vector adding/doubling method [*De Haan et al.*, 1987; *Chowdhary*, 1999]. We ignore gaseous absorption, and use the molecular optical thickness given by *Hansen and Travis* [1974] with a scale height of 8km.

3. Retrieval Results and Discussion

We use the radiances and polarized radiances measured by the RSP to retrieve all parameters of the coarse and fine aerosol modes, including the spectral refractive index (m _), the effective radius (r_{eff}) and effective variance (v_{eff}) of the log normal size distribution, the contribution to the total spectral optical thickness (_ _), and the column number density of particles (*N*) in each mode. We then examine how well these parameters could be constrained by the appropriate subsets of the RSP measurements that would represent data available from MODIS, MISR, and POLDER. Our retrieval algorithm uses measurements at 2.250 µm to provide an estimate of the coarse mode properties under the assumption that the fine mode aerosol optical thickness at 2.250 µm is much smaller than that of the coarse mode. Once an estimate of the coarse mode properties has been obtained, it is used, together with the 0.865-µm measurements, to estimate the parameters of the fine mode. This initial guess is then used as the starting point in a non-linear iterative search, using the Levenberg-Marquardt method [*Ortega and Reinbolt*, 1970] coupled to vector radiative transfer calculations, which converges rapidly (3-5 iterations) to a solution that is consistent with all the measurements used in the fitting process given their known uncertainties. The magnitude of these uncertainties that are caused by calibration and noise are shown on each of the panels in Fig. 1. The uncertainties in the retrieved bimodal parameters shown in Table 2 are 95% confidence intervals based on the diagonal elements of the covariance matrix of the aerosol model parameters at the last step in the iterative search [*cf. Rodgers,* 1976]. The uncertainties in optical depth and column number concentration for each mode are strongly correlated and so a more useful estimate of the uncertainty in the retrievals is provided by the uncertainty in total optical depth (±0.008), the relative uncertainty in column number concentration of the two modes (10%) and the uncertainty in total column number concentration (25%). It is important to note that if the initial assumption of spherical particles were not true, it would be impossible to achieve a satisfactory fit to the measurements [*Mishchenko et al.,* 1997b]. In such a case (e.g. coarse mode is dust) we would then use computations of light scattering by shape distributions of polydisperse spheroids to represent the nonspherical particles. A comparison between the optical depths measured by multi-filter rotating shadowband radiometers (MFRSRs) [*Schmid et al.,* 1999] and inferred from polarimetry is shown in Fig. 2 for 14 October 1999 (Oxnard, CA) and 31 March 2000 (Goleta, CA), with optical depth differences at 0.55µm of –0.01 and 0.008 respectively. Since the spectral slope of the inferred optical depth depends on the retrieved size distribution and since the shortest wavelength used in the RSP retrieval is 0.865 µm, the good fit over this spectral range is indicative of the quality of the size distribution retrieval.

Panels 1(a) and 1(b) show results for the data set acquired on 14 April 1999 at 5:31 PM near Morro Bay. Panel 1(a) shows the reflectance $I\pi/\mu_0F$ and panel 1(b) shows the polarized reflectance $(Q^2+U^2)^{1/2}\pi/\mu_0F$ as a function of viewing angle θ_V, where $\mu_0 = \cos\theta_0$ is the cosine of the solar zenith angle and F is the extraterrestrial solar irradiance (θ_0=66.3°, azimuth angle difference $\phi-\phi_0$=0.3° for positive view zenith and $\phi-\phi_0$=180.3° for negative view zenith angles). The sharp increase in reflectance at $\theta_V >$ 25° at both wavelengths is caused by the sunglint. The strong sensitivity of the sunglint angular profile to wind speed and the wide dynamic range of the RSP allowed us to reliably constrain the wind speed value (3.3 m/s). We obtained the best fits [shown by squares in panels 1(a) and 1(b)] to the RSP measurements using the coarse and fine mode parameters listed in Table 2. Although the assumption that the aerosols are non-absorbing can be relaxed (single-scattering albedo of 0.94±0.06 and 5% increase in optical depth), except for very strongly absorbing materials, the scattering matrices of particles are not very sensitive to the imaginary part of the refractive index. It is therefore not possible to partition the inferred absorption, between the imaginary refractive index of the two aerosol modes and small absorbing soot particles that are externally mixed, with any degree of certainty. Nonetheless, the retrieved real refractive indices and their spectral variation are indicative of those expected for sea salt (coarse mode) and water soluble particles (fine mode) [*D'Almeida et al.,* 1991] and this type of information will quite often be sufficient to permit a reasonable inference of the aerosol composition.

Panels 1(e) and 1(f) show that data acquired 10 minutes later above the Santa Barbara Channel, ~30 km to the south-east from the first site (θ_0=68.6°, $\phi-\phi_0$=173.8°), can be well reproduced using the same aerosol model, but with the optical thicknesses adjusted, coarse mode reduced by 5% and fine mode increased by 15%, and the wind speed increased to 3.7 m/s (squares). The remarkable ability of the RSP measurements to constrain the aerosol model is demonstrated by calculations assuming a small increase (Δm = 0.03) in the coarse mode refractive index. Panel 1(e) shows that the resulting change in the total reflectance in both channels can be compensated for by a decrease in the coarse mode optical thickness (triangles). However, the fit to the polarized reflectance becomes significantly worse [triangles in panel 1(f)], especially in the 2.250-µm channel. In particular, polarization calculations at 2.250 µm exhibit a neutral point at ~43° not seen in the measurements. Diamonds in plate 1(e) show that even larger errors in the refractive index (Δm = –0.09) can still be compensated for by changing the optical thickness so that the intensity measurements are again nicely matched, while polarization measurements clearly rule this wrong solution out [diamonds in panel 1(f)]. This illustrates that even by combining radiance measurements from instruments such as MISR and MODIS one cannot retrieve the aerosol refractive index (and hence composition), and that assuming the refractive index *a priori* translates into significant errors in other retrieved parameters, e.g., optical thickness.

Panel 1(c) shows that radiance measurements near Morro Bay in both spectral channels can be well reproduced using monomodal rather than bimodal size distributions. The best-fit parameters of two acceptable monomodal size distributions (hereafter referred to as "mono-1" and "mono-2" models) are listed in Table 2. Uncertainties in these size distribution parameters are not given since this analysis represents a paper in itself [*Mishchenko and Travis,* 1997], but, since these two monomodal size distributions cannot be differentiated using intensity measurements, the uncertainties are at least as large as the differences between the two size distributions. This result means that radiance-only measurements would fail to differentiate monomodal from bimodal aerosol populations or distinguish between various monomodal distributions, translating into significant retrieval errors. For example, the total aerosol optical thickness retrieved using the two monomodal distributions is significantly different from that retrieved using the correct bimodal distribution, and the particle column number density found for the mono-1 (mono-2) model is a factor of 1.9 larger (a factor of 3.4 smaller) than that retrieved for the bimodal distribution (Table 2). The non-uniqueness problem faced by intensity-only measurements has been shown to persist even when a wider spectral range is available [*Tanré et al.,* 1996], but can be mitigated to some extent by adding polarization measurements at 0.865 µm (POLDER) which enable one to distinguish between the mono-1 and mono-2 models [panel 1(d)]. However, the mono-1 model still reproduces the polarization at 0.865 µm with accuracy similar to that of the correct bimodal distribution, which is indicative of the non-uniqueness problem faced by POLDER with its relatively narrow spectral coverage. It is only by including the 2.250 µm polarization data that one has sufficient information to unambiguously determine that the aerosol population is not monomodal and to determine the size distribution parameters of the two modes.

4. Conclusions

Using data obtained over the ocean by an airborne version of EOSP we show that bimodal aerosol size distribution, composition (via real refractive index), optical depth, and number density can be retrieved from multi-spectral, multiangle polarization measurements. We note also that MISR-, MODIS- and POLDER-type subsets of our data would not be able to distinguish multimodal aerosol distributions from monomodal nor would they have useful sensitivity to the real refractive index. Only accurate polarimetric measurements made over a broad angular and spectral range allow us to resolve the non-uniqueness problem and thus determine aerosol parameters with the accuracy needed for long-term monitoring of the direct and indirect aerosol forcings of climate.

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B. Cairns, J. Chowdhary, M. Mishchenko, and L. Travis, NASA GISS, 2880 Broadway, New York, NY 10025. (bcairns@giss.nasa.gov, jchowdhary @giss.nasa.gov, mmishchenko@giss.nasa.gov, ltravis@giss.nasa.gov)

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[1]Also at the Department of Applied Physics and Applied Mathematics, Columbia University, New York.

Table 1. Comparison of capabilities of five instruments for tropospheric aerosol remote sensing.

Instrument	Number of bands	Spectral[a)] range	Number of view angles	Type[b)] of data
AVHRR	2	0.650 to 0.850	1	I
MODIS	7	0.470 to 2.130	1	I
MISR	4	0.443 to 0.865	9	I
POLDER	4[c)]	0.443 to 0.865	<14	I,P
EOSP	7[d)]	0.410 to 2.250	152	I,P

[)] in μm; [b)] I = Intensity, P = Polarization; [c)] 3 for P; [d)] 7 for P.

Table 2. Aerosol parameters retrieved from various RSP data (sub)sets.

Aerosol	r_{eff}[a)]	v_{eff}	m_{2250}	m_{865}	$_{550}$[b)]	N[c)]
coarse	1.0 ± 0.10	1.0 ± 0.10	1.39 ± 0.01	1.45 ± 0.02	0.035	3.4×10^{10}
fine	0.1 ± 0.03	0.2 ± 0.02	1.35 ± 0.02	1.45 ± 0.01	0.049	6.7×10^{12}
mono-1	0.25	2.0	1.32	1.39	0.121	1.3×10^{13}
mono-2	0.35	1.5	1.37	1.48	0.094	2.0×10^{12}

[a)] in μm; [b)] taking $m_{550} = m_{865}$; [c)] in m^{-2}.

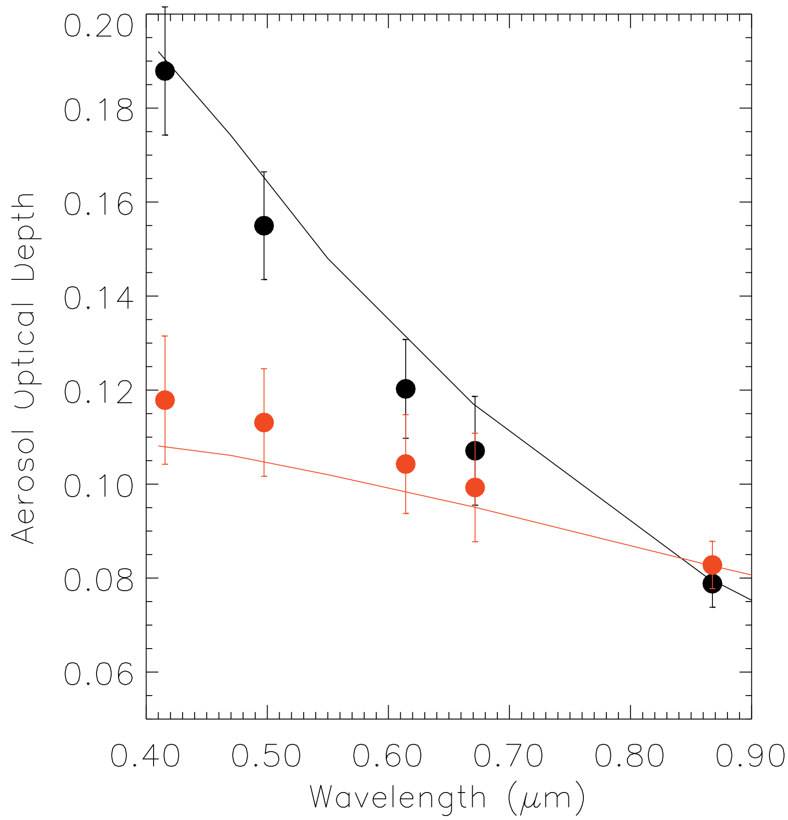

Figure 1. RSP data taken over the ocean off the coast of California (solid curves) and results of simulations (symbols). The upper and lower rows are for the total and polarized radiances, respectively. Green and red curves depict 0.865 and 2.250 μm data, respectively. Left column: Curves show the data obtained over Morro Bay. Squares demonstrate theoretical fits using the bimodal size distribution with the coarse and fine modes specified in Table 2. Middle column: Squares and triangles show model fits to the same data using mono-1 and mono-2 aerosols, respectively, as specified in Table 2. Right column: Curves depict the data obtained over the Santa Barbara Channel. Squares show fits obtained with the same bimodal aerosol as in the left column but with the optical thicknesses adjusted, coarse mode reduced by 5% and fine mode increased by 15% (squares). Triangles (diamonds) demonstrate the result of increasing (decreasing) the coarse mode refractive index by 0.03 (0.09) and adjusting the optical thickness so that the total radiances could still be reproduced. Yellow circles highlight measurement error bars.

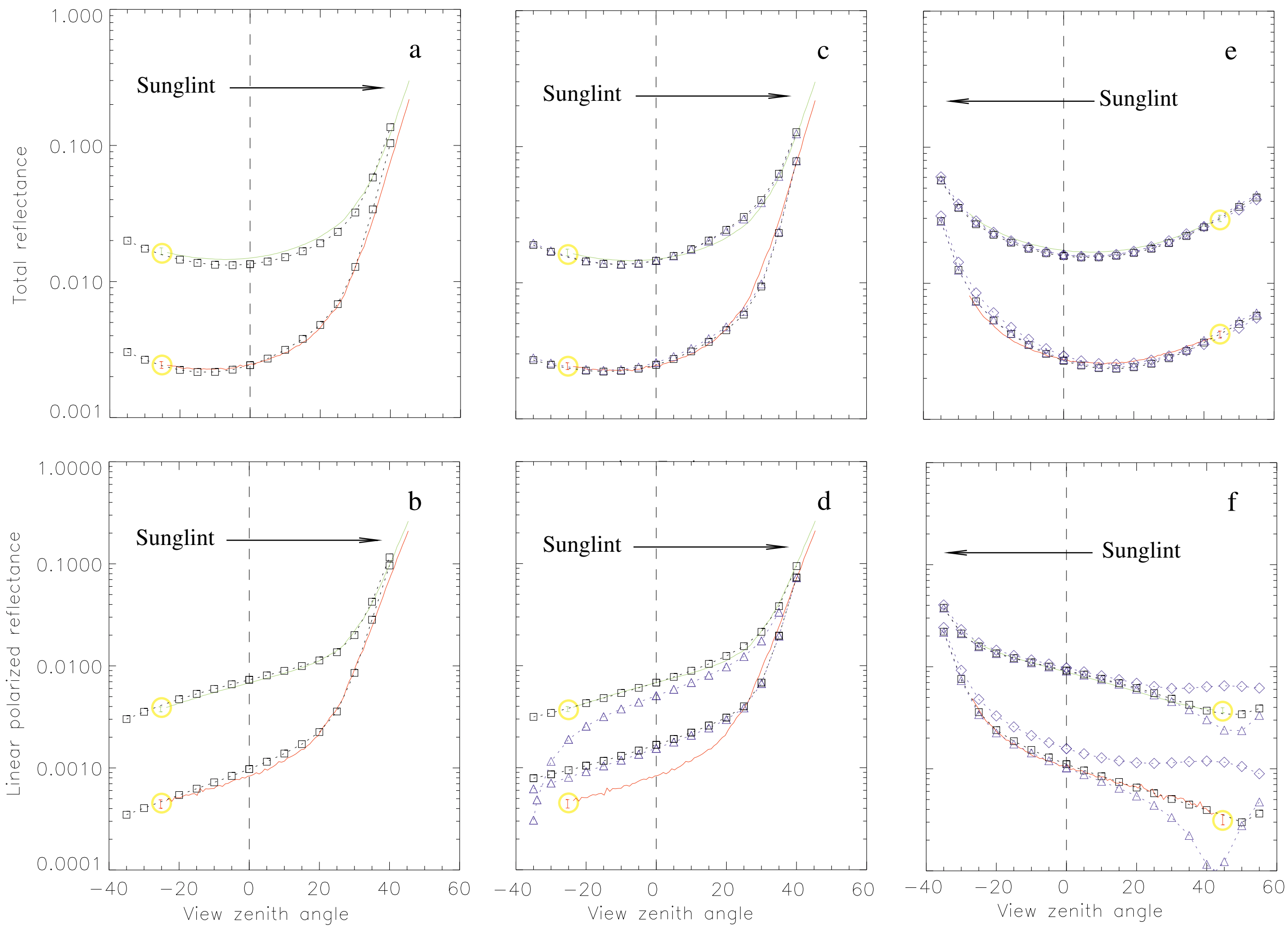

Figure 2. Optical depth comparison. MFRSR measurements for 14 October 1999 are shown as black filled circles and for 31 March 2000 as red filled circles. Spectral dependence of aerosol optical depth inferred from polarimetry measurements on these two days are shown by solid curves. Error bars are only shown for the MFRSR measurements.